Lunar gamma-ray emission observed by FERMI-LAT as a probe to study the solar cycle

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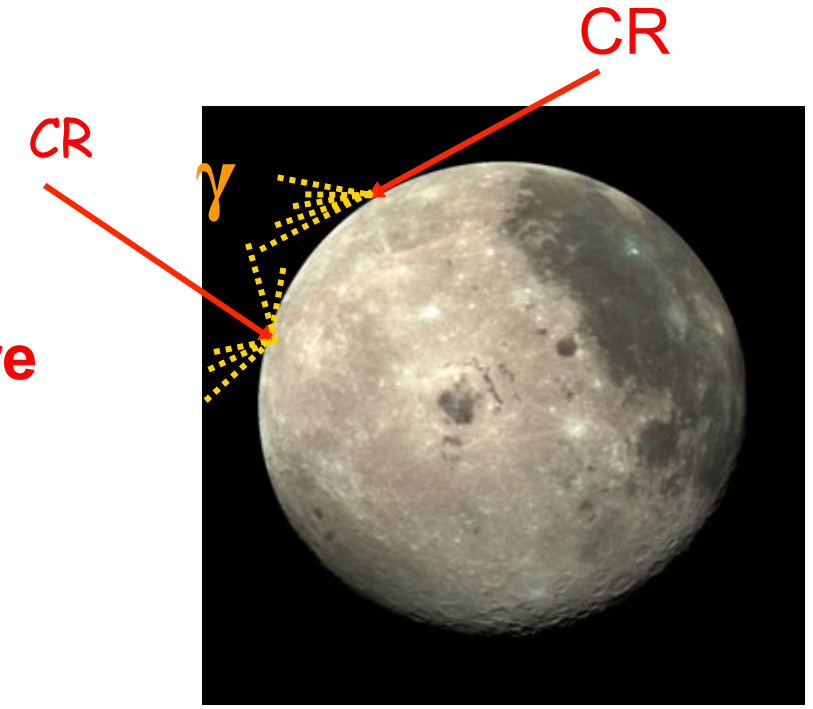
Gamma-Ray Sources in Solar System

- Sources (in red those dected by ***Fermi*-LAT**):
  - The Moon (**ApJ, 758, 140, 2012**)
  - The Sun (**ApJ 734, 116, 2011**)
  - The Earth (**Phys. Rev. D, 80, 122004, 2009**)
- Potential Sources
  - Asteroids in different populations:
    - Main Asteroid Belt (MBAs)
    - Jovian and Neptunian Trojans (Trojans)
    - Kuiper Belt Objects (KBOs)
  - Other planets

Emission Mechanisms in solar system bodies

γ-ray in solar system are produced as secondary emission due to CR interactions with surface material of different bodies:

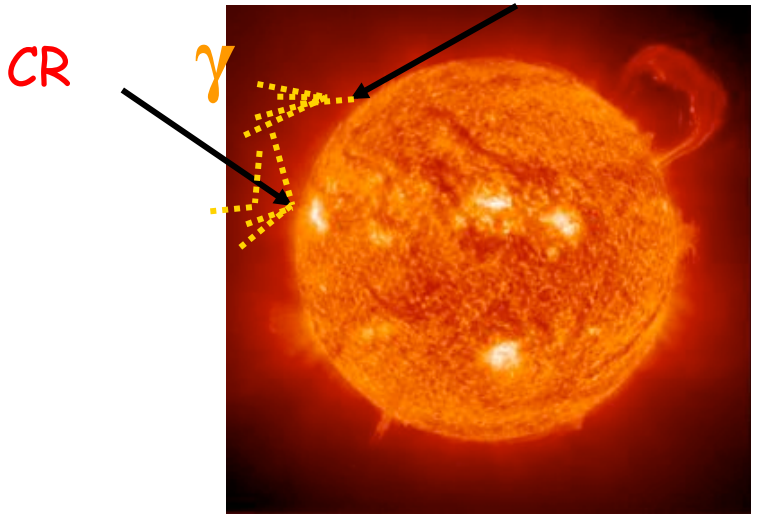
- **Moon rock**
- **Solar disk+ solar photosphere (IC mechanism)**
- **Earth atmosphere**



Quiet Sun: Emission mechanisms

Sun has two mechanisms for gamma-ray production:

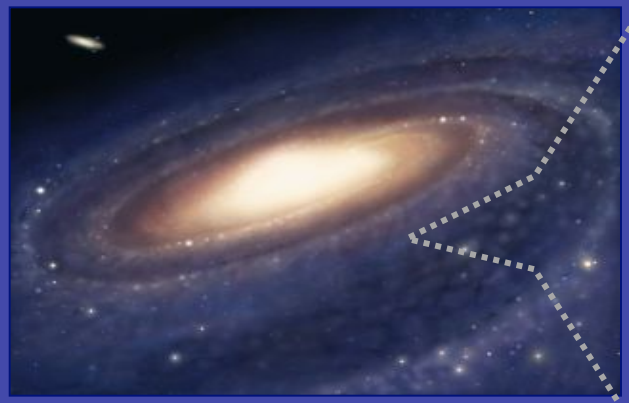
Hadronic interactions of cosmic rays with the solar surface

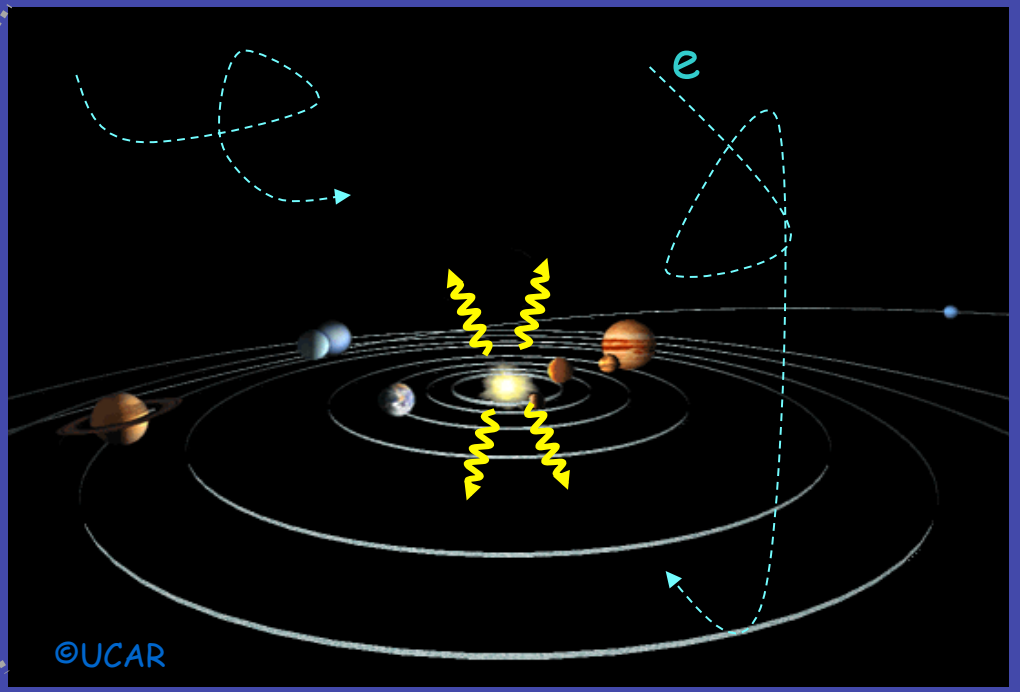


This component is therefore localized in the solar disk (almost pointlike)

Gamma-ray flux ➔ cosmic-ray flux

Sun: second component
Inverse Compton Scattering





Inverse-Compton scattering of solar photons in the heliosphere by Galactic CR electrons: the emission is extended

- Electrons are isotropic
- Photons have a radial angular distribution

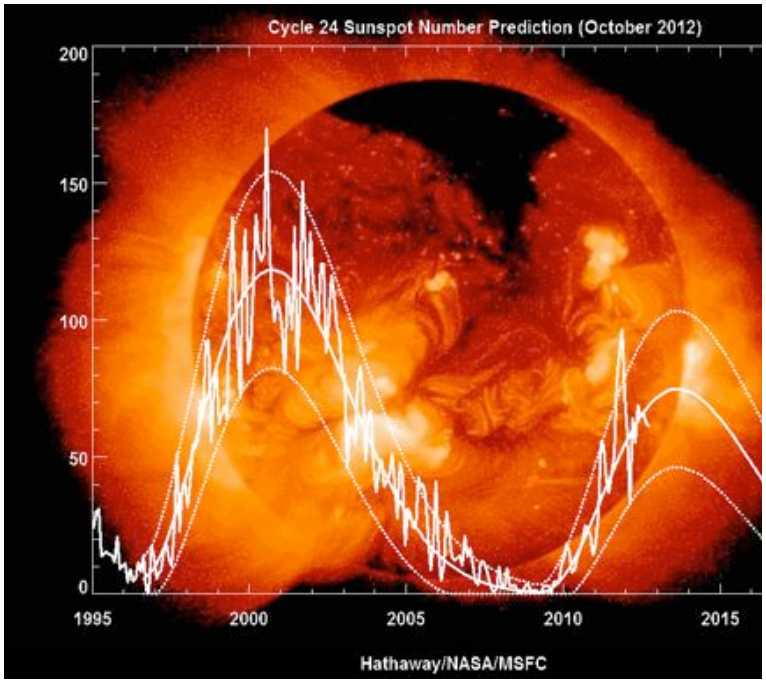
Moskalenko '06

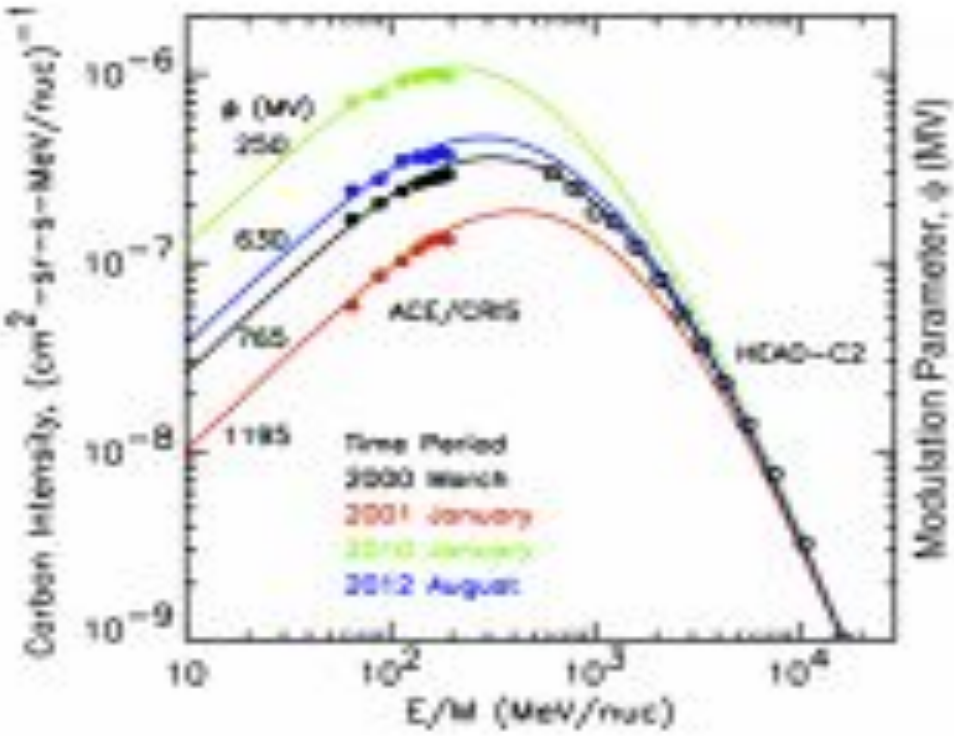
Otlando&Strong astro-ph 0607563

Orlando&Strong'07

Cosmic-ray modulation

Max solar activity -> min cosmic-ray flux
Min solar activity -> max cosmic-ray flux
Indirect measurements are the only way
to trace CRs in inner heliosphere and outside the geomagnetic field!





- **Solar Activity is now going to the maximum**
- **Fermi operates for nearly the entire duration of solar cycle 24**

See http://www.srl.caltech.edu/ACE/ACENews_curr.html

LAT data selection and main cuts

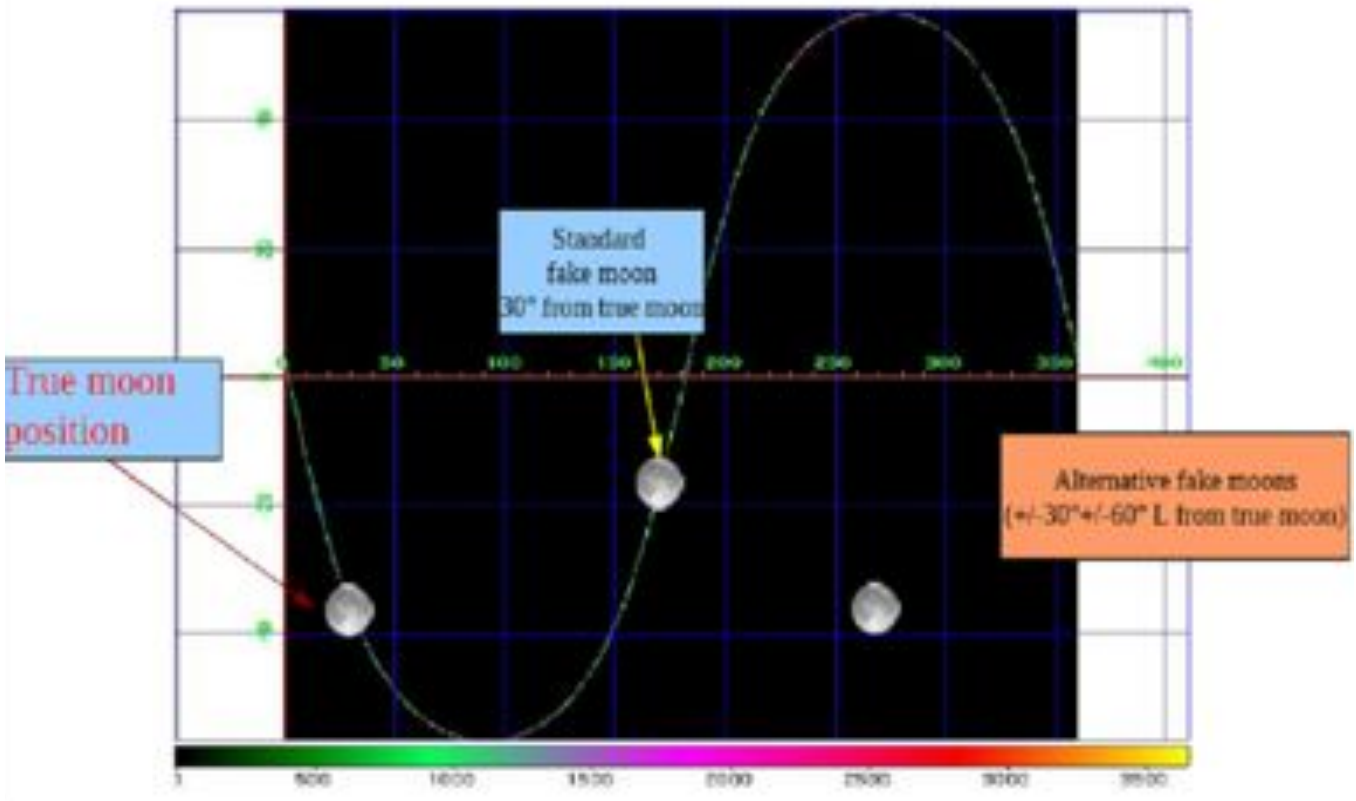
- 3 years data , PASS7 IRFS
- Analysis in Moon-centered frame
- Zenith angle < 100°
- Galactic Plane Cut (|b|>30°) (to reduce the diffuse galactic background)
- Moon-Sun angular separation >20°
- Parallax corrections applied

Background estimation

The trial sources method:

Averaged flux from several trial sources following the real moon along the same sky path but >30 degrees away:

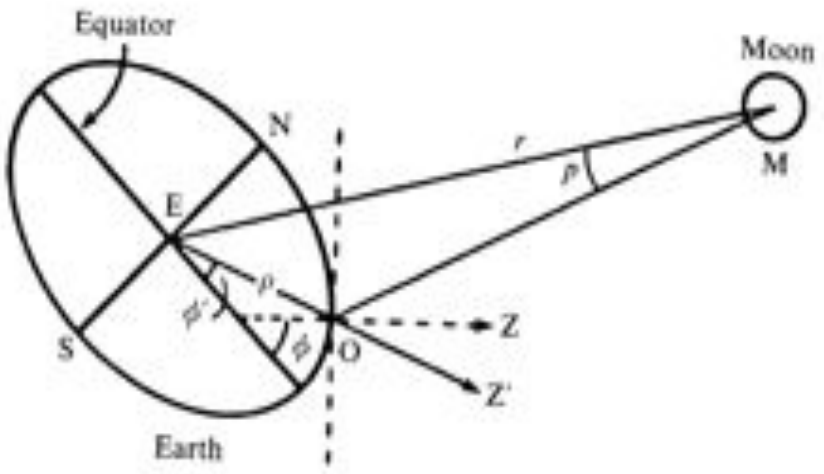
In this way the description of the diffuse emission for the same regions crossed by the Moon is easily computed



Main systematic effects on this observation

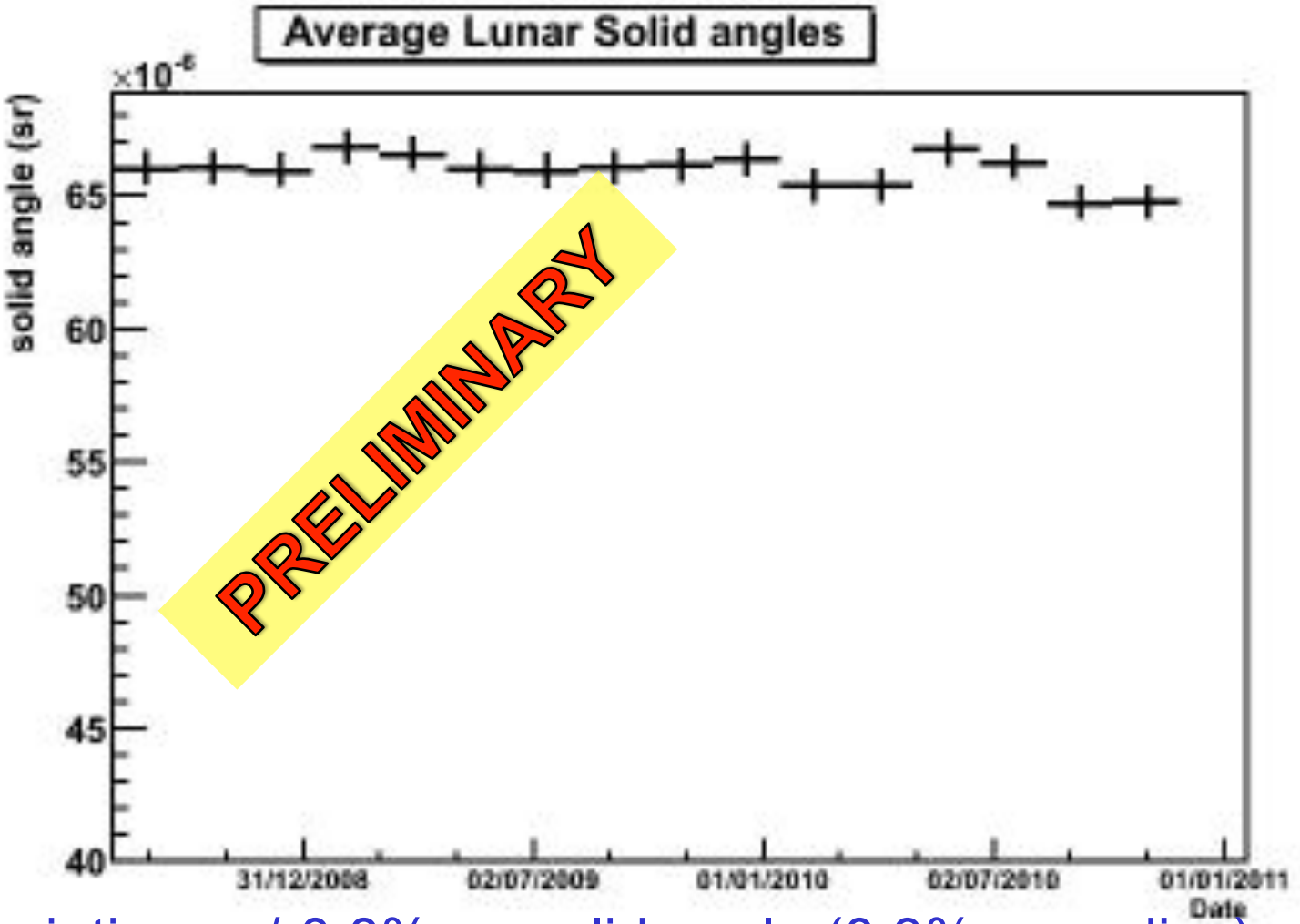
- **Moon is moving fast in the sky ->Moon centered frame + background estimation using trial source way**
- **Moon is moving on its monthly orbit around the Earth, so the average distance and the apparent diameter change ->take into account the average diameter or choose temporal interval selections to minimize the effect**
- **We choose 2 month duration as the basic interval to evaluate the changes of lunar flux**

Evaluating Moon-LAT apparent radius



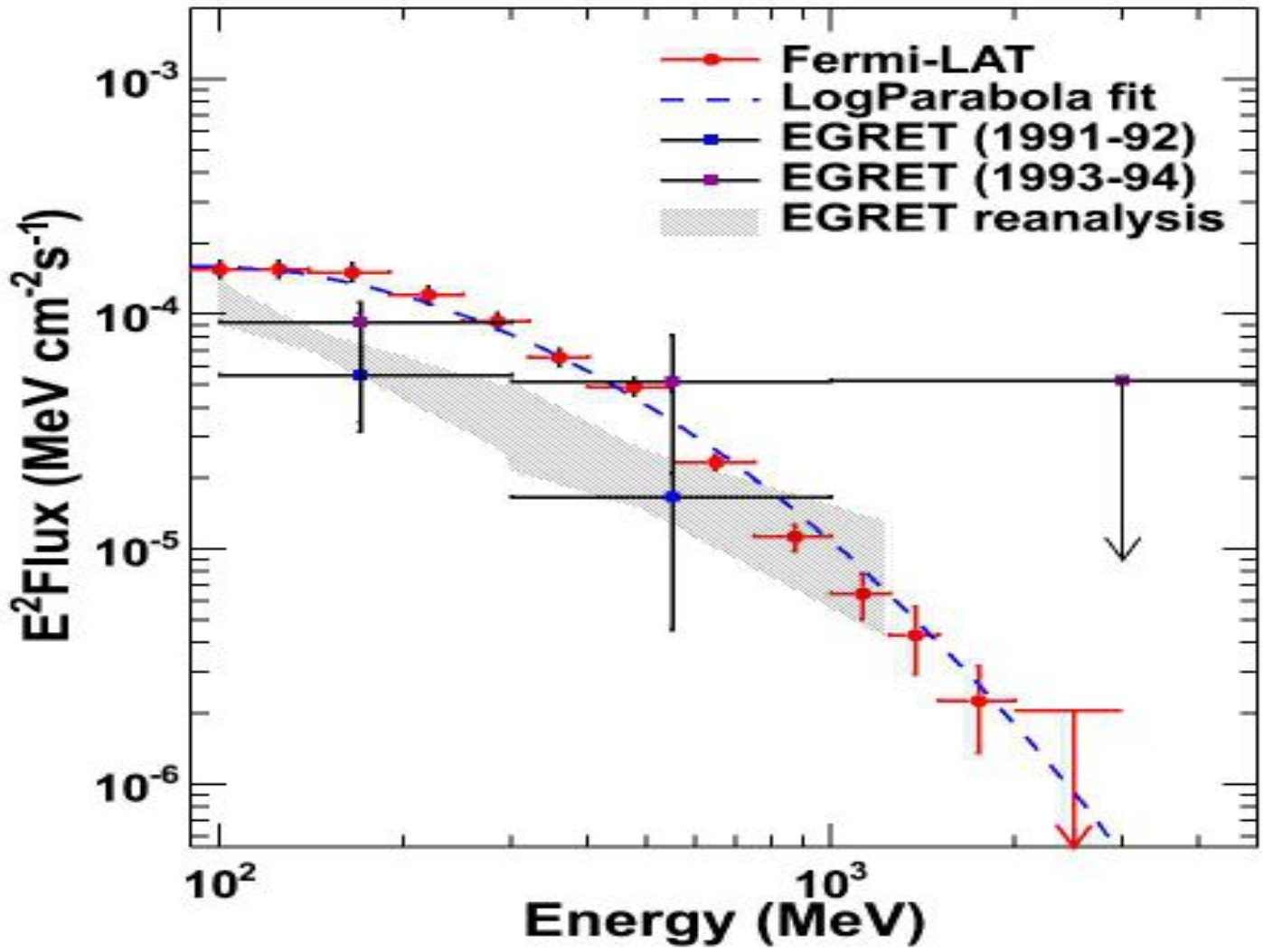
Same problem was solved to compute parallax corrections: when matching ft1 and ft2 infos is possible to evaluate the apparent lunar radius seen by LAT using a bit of trigonometry; spacecraft positions and lunar positions are necessary

Average radius each month



Max variations +/-0.8% on solid angle (0.3% on radius)

Lunar spectrum (3years) from the paper (ApJ, 758, 140 2012)



Analysis results

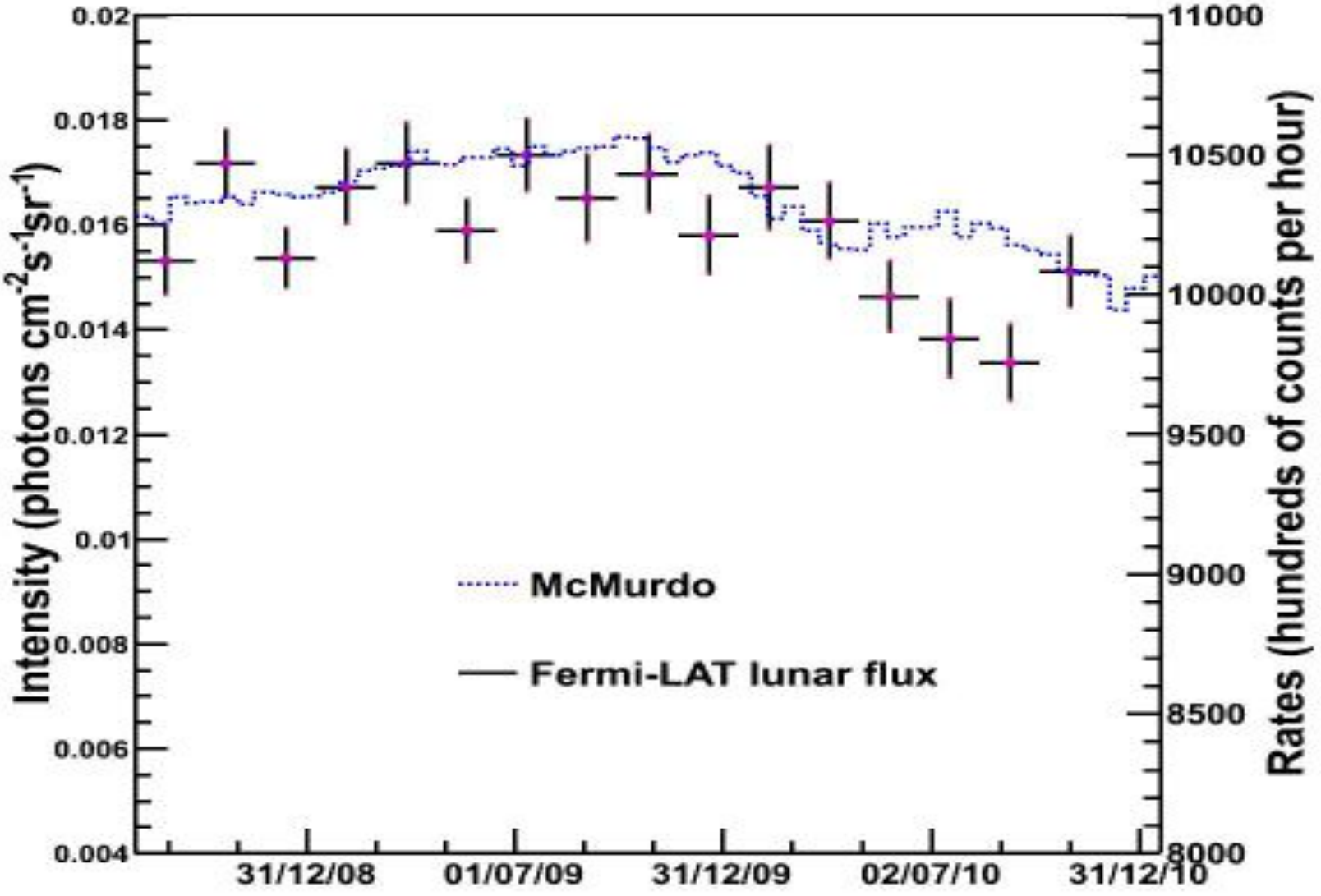
- **The spectrum is well fitted by a logParabolic function**
- **Φ(E>100MeV)= (1.04±0.01(stat)±0.1(sys)))•10^{-6} $cm^{-2}s^{-1}$**
- **Have we the sensibility to the apparent diameter changes?** YES!

We found that an average variation of ±3% implies a flux variation of ± 6% as expected due to the solid angle change

Lunar flux measurements and solar modulation

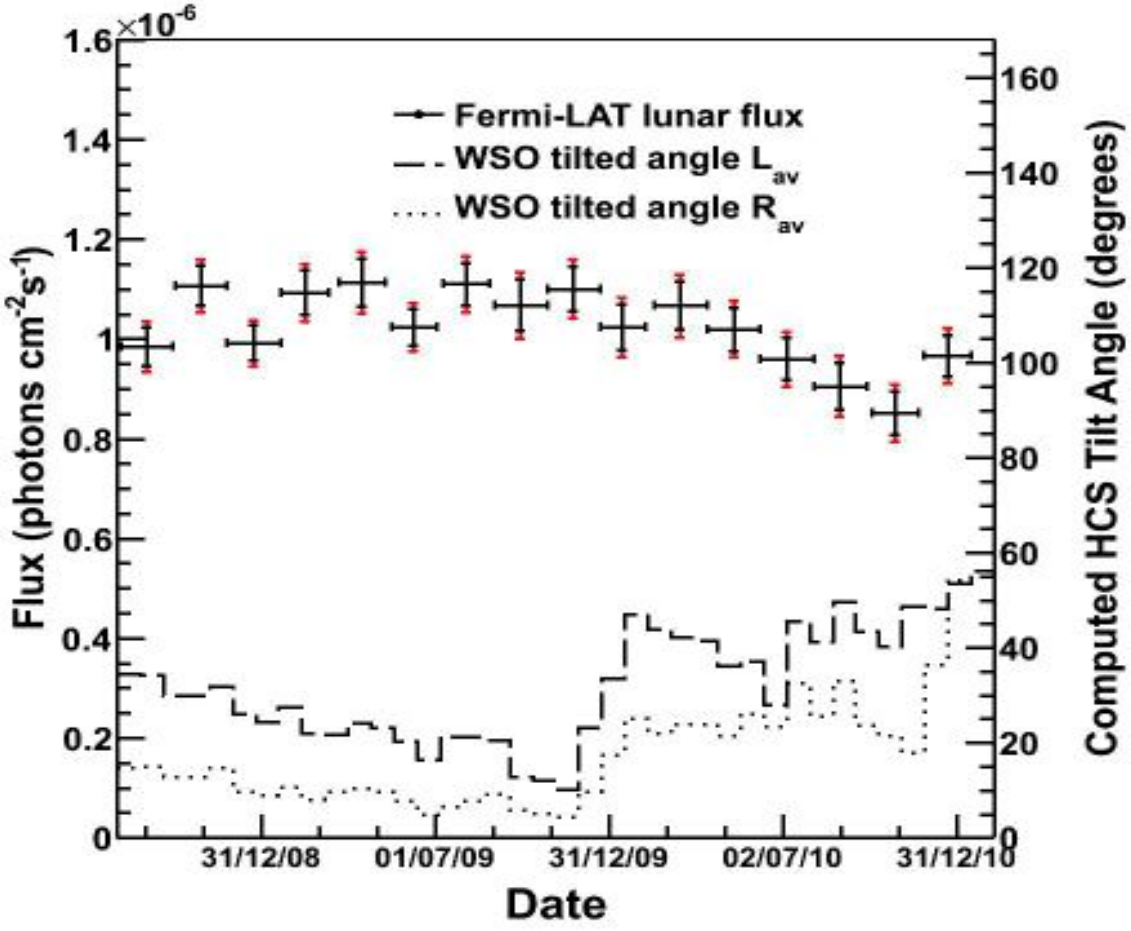
- **Are the lunar flux measurements by LAT sensible to the solar cycle evolution? Maybe**
- **We have to find a compromise between statistical significance and time intervals selections having minimal systematic effects**
- **In this first analysis we choose 2-months intervals as the best compromise**
- **Comparison with neutron monitor fluxes and observed tilt angles to see some qualitative correlation**

Neutron monitor rates and Lunar emission



NM data from http://neutronm.bartol.udel.edu/

Lunar Flux vs heliospheric current sheet tilt angles



http://wso.stanford.edu/Tilts.html

Summary

- ✓ **Some evidence of correlated fluctuation of lunar gamma-ray emission and NM rates confirm that the solar activity acts is modulating the CR fluxes**

- ✓ **Lunar emission monitoring can be used to compensate the lack of direct measurements on solar modulation outside the geomagnetic field**

- ✓ **To study the correlation is necessary to keep any systematic error at minimum and using good compromise between time intervals and statistics**

- ✓ **Variations due to the low energy photons may be different than those detected in NMs**

Extra slides

Apparent radius changes for the 3 years sample

Lunar apparent radius seen by LAT using the GTIs